Semiannual Progress Report No. 13

A STUDY OF SELECTED RADIATION AND
PROPAGATION PROBLEMS RELATED TO ANTENNAS
AND PROBES IN MAGNETO-IONIC MEDIA

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Antenna Laboratory
Department of Electrical Engineering
Engineering Experiment Station
University of Illinois
Urbana, Illinois 61801

Table of Contents

1. INTRODUCTION

This semiannual report covers the activities in the period from April 1, 1969 to December 1, 1969.

A survey report of publications on the problem of antenna impedance in a plasma has been completed and will be distributed shortly [2.1].

The current distribution on a thin conducting antenna in a magneto plasma is being computed by numerical methods [2.2].

The experimental study of the short dipole in a magneto plasma has been continued during the summer. Some unexpected effects have been observed and a thorough reinterpretation of previous results will have to be conducted [2.3].

The problem of radiation from a waveguide into a layered plasma medium has been solved by a new method. The results should be useful in evaluating measurements taken with a slot antenna. This effort is completed [2.4].

The noise experiment requires much careful preparation. A new tube has been constructed. The magnetic coils have been completed and tested [2.5].

Diagnostic and remote probing lead directly to "inverse problems" where the medium properties, in general non-uniform, are to be deduced for example from measurement of reflections (scattering, impedance...) as a function of frequency or incidence angle. New methods of "optimization" are being applied to these problems. Initial results are encouraging [2.6].

2. SUMMARY OF RESEARCH

2.1 Literature Survey: Theory and Experiments on Antennas in Plasmas – S. W. Lee and M. Al-Hakkak

The goal of the survey was to review the large number of papers that were published in the past few years on the topic of antennas in plasmas and, in particular, theoretical and experimental papers on cylindrical or wire antennas.

The survey has been completed and a technical report will be issued shortly.

2.2 Cylindrical Antenna in a Magnetoplasma – P. Klock and G. A. Deschamps

A theoretical study to find the current distribution on a thin linear antenna with arbitrary excitation in an infinite, homogeneous and cold magnetoplasma is being considered.

The approach currently being used is the method of moments. The antenna is partitioned into subsections small in terms of wavelength. On each subsection a uniform current of unknown magnitude and phase is assumed to be flowing along the surface in the direction of the axis of the antenna (thin wire approximation). The electric field is computed from each current and the total electric field from all currents is set equal to the negative of the exciting field at the center of the subsection resulting in a set of linear algebraic equations for the magnitude and phase of the currents in each subsection.

The computation of the electric field from the current in one subsection is particularly involved due to the medium being anisotropic. A technique of computing the fields of a dipole source in a magnetoplasma suggested by Mittra and Deschamps is being used. In this method the singular terms (ones which become infinite as the antenna axis is

approached) are computed in closed form and the finite terms are computed in terms of an integral. The finite terms are not expressible in finite combination of the elementary functions.

At present the expression for the field in Z direction from a Z directed current have been obtained. The strong steady magnetic field is in the Z direction. Some progress has been made in the evaluating parts of the Z directed fields with aid of a digital computer.

It is anticipated that the fields will be computed and the set of linear equations found for the unknown currents. This set of equations will be solved by inverting the matrix of coefficients to find the currents for the given arbitrary excitation.

2.3 Impedance of a Short Dipole in a Magnetoplasma - R. J. Kostelnicek and R. Mittra

A. Introduction

Both d.c.-probe and small impedance measurements were conducted on an electrically short balanced dipole in a laboratory plasma with and without a d.c. magnetic field. Three orientations of the probe antenna with respect to the magnetic field were employed for the d.c. probe measurements, and only one orientation for the impedance measurements.

B. Direct Current Probe Measurements

Langmuir probe measurements were carried out by employing a parallel connection of the antenna center conductors biased relative to the anode of the discharge tube. The impetus for such measurements was to become familiar with the discharge characteristics. It was hoped that some knowledge of the plasma frequency could be obtained; however, this was

not the case. Instead, some interesting probe characteristics were encountered. It was found that without careful scrutiny on the part of the experimentalist, the d.c. characteristics could lead to erroneous conclusions.

Figures 1 through 3 show Langmuir probe characteristics for three probe orientations; 0, 45, and 90. Note the "too typical" shape of the characteristic of the 90 curve. At first sight, one suspects almost a perfect Boltzmann behavior in the electron accelerating region of the curve due to the linear behavior as plotted on semi-log paper. However, for the orientations of 45 and 0 one finds a departure from this linear behavior.

The 90 curve also indicates a textbook behavior in the electron saturation region. However, a comparison with similar characteristics for different discharge current and gas pressures reveals that, as is the case in Figure 3, the d.c. probe current in the saturation region was always asymptotic to the d.c. discharge tube current. Placing an ammeter in the anode circuit revealed that the sum of the probe current and anode current was a constant and equal to the anode current with the probe biased deep in the electron retardation region. The conclusion seems to be that the probe acts as a partial anode. In fact, when the probe is biased three volts or more positive relative to the actual anode, the probe receives the total discharge current and is, in fact, the anode of the discharge itself. Figures 1 and 2 indicate that, as the antenna axis are brought closer toward coincidence, the probe behaves less like an anode and the result is a degradation of the Langmuir probe characteristic. The current collected by the antenna seems to be directly related to the area projected by the probe on a phase normal to the tube axis.

4

The above observations suggest that the probe may be too large for the cross sectional area of the present discharge tube, since the probe has a severe influence on discharge current. Whether the local plasma conditions are altered or not is not evident, since it may well be that the d.c. probe characteristic due to the random plasma current is obscured by the discharge-current-capture effect of the probe.

Displayed in Figure 4 are Langmuir probe characteristics for three different axial magnetic fields. The current in the field coils are given as I_B instead of the actual field intensity. The effect of increasing the axial magnetic field on each probe orientation was to decrease the probe current collection. This decreasement seems to be in line with a channeling of the random current density along the magnetic field lines, and thereby reducing the effective area of the probe.

C. Radio Frequency

Due to the unfaithfulness of the Langmuir probe measurement, an alternative approach was employed to determine the plasma frequency. One half of the dipole antenna was employed as a transmitting antenna, while the other half was used for receiving. In general, it was found that there was a marked change in transmission through the plasma between 250 and 600 MHz depending on the discharge current and gas pressure. Figure 5 shows the plasma frequency f_p for several values of discharge current and gas pressures. Although we have no means of assessing the accuracy of these measurements, we note in general that the plasma frequency, as determined by this data, increases with both gas pressure and discharge current, these results being in line with the theory.

Antenna admittance measurements were carried out for various probe biases and values of magnetic field. In general, it was found that the admittance loci had a zero reactance cross-over between 800 and 900 MHz; however, this cross-over was independent of probe bias as indicated by Figures 6 and 7. Probe biases more positive or negative than those of Figures 6 and 7 show little change. The probe orientation in these measurements was 90°.

Figures 8 through 11 show the effect of an increase in the magnetic field. That effect is to rotate the admittance loci clockwise, and therefore, remove the isotropic plasma admittance resonance.

D. Conclusion

No attempt was made to obtain admittance measurements of probe orientations other than 90, since d.c. probe measurements indicated that the probe itself played a significant role in the discharge cir- cuitry. Therefore, it was assumed that the local plasma conditions were severly effected by probe bias.

Although little R.F. information was obtained, significant d.c. information was realized. We caution experimenters that a well defined saturation of the Langmuir probe characteristic could lead to erroneous electron density information, since, as was observed for a relatively large probe as compared to tube diameter, this saturation merely indicates that the probe has become the tube anode.

A number of impedance measurements taken in the Spring 1969 and not reported previously are being reanalyzed to take into account the present results.

Figure 1

Orientation 0°

P = 100µ

B = 0

$I = 1_{ma}$

Figure 2

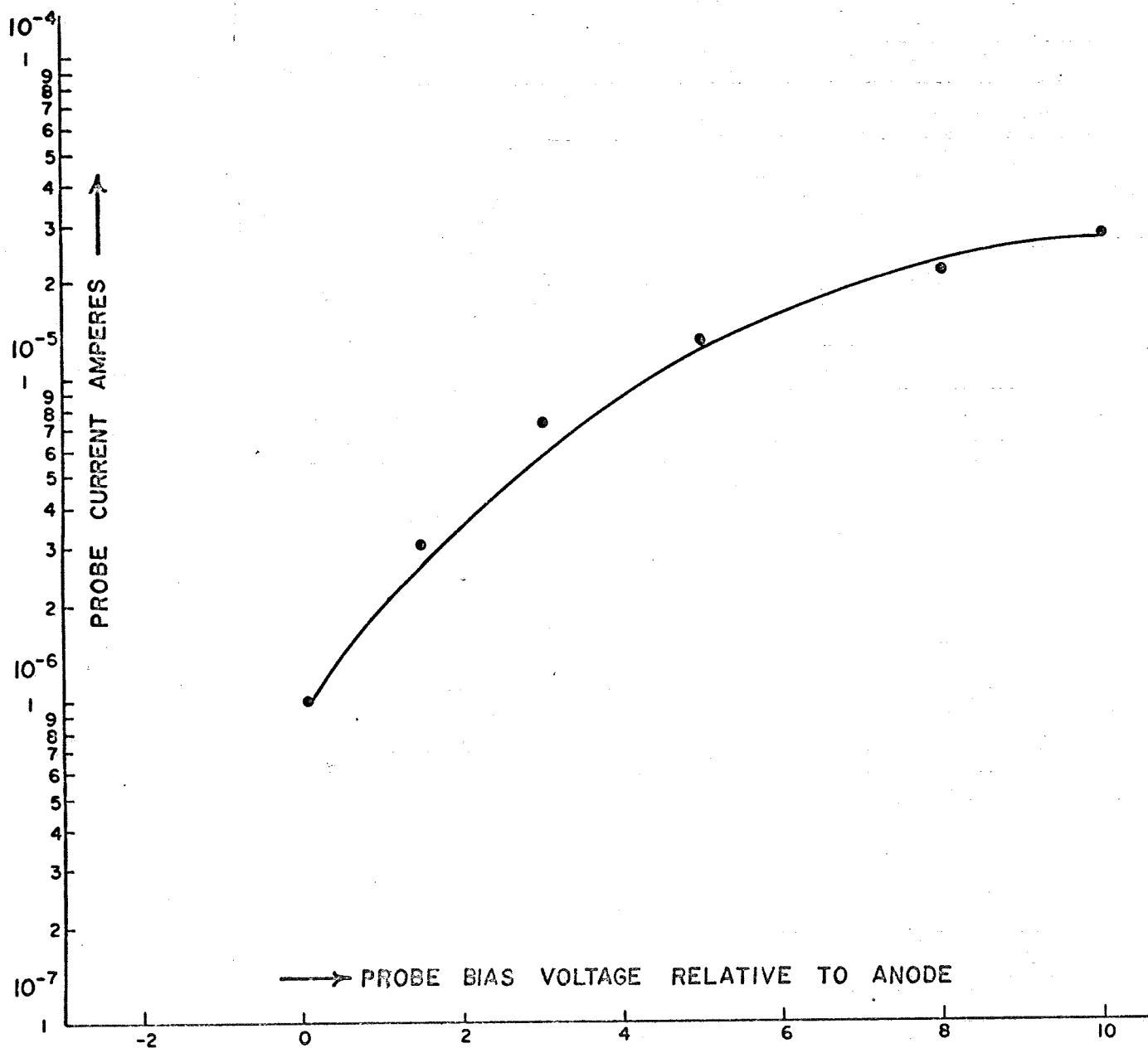Orientation 45°

$P = 100\mu$

$B = 0$

$I = 1_{ma}$

8
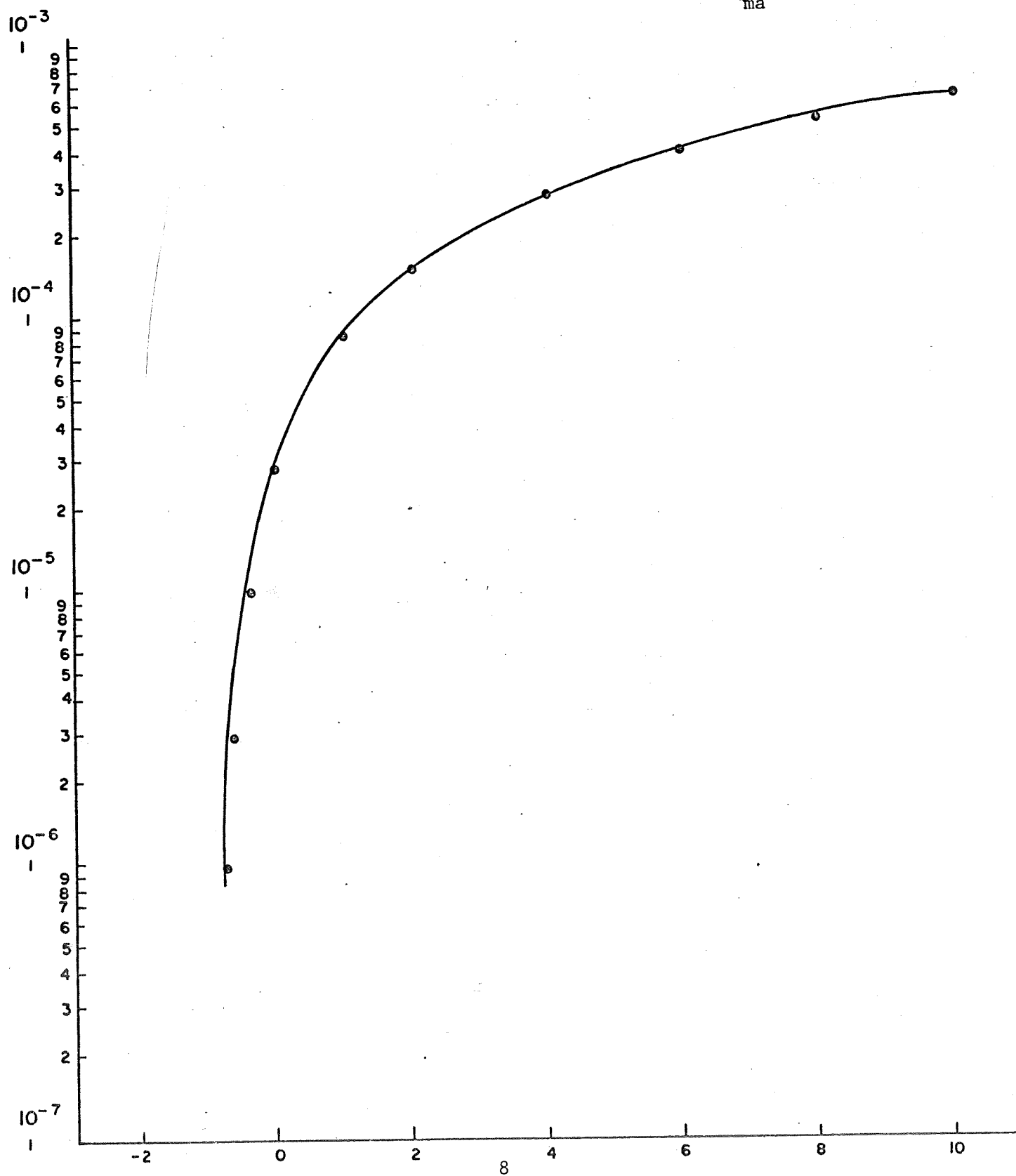
Figure 3

Orientation 90°

P = 100μ
I = 1 ma
B = 0
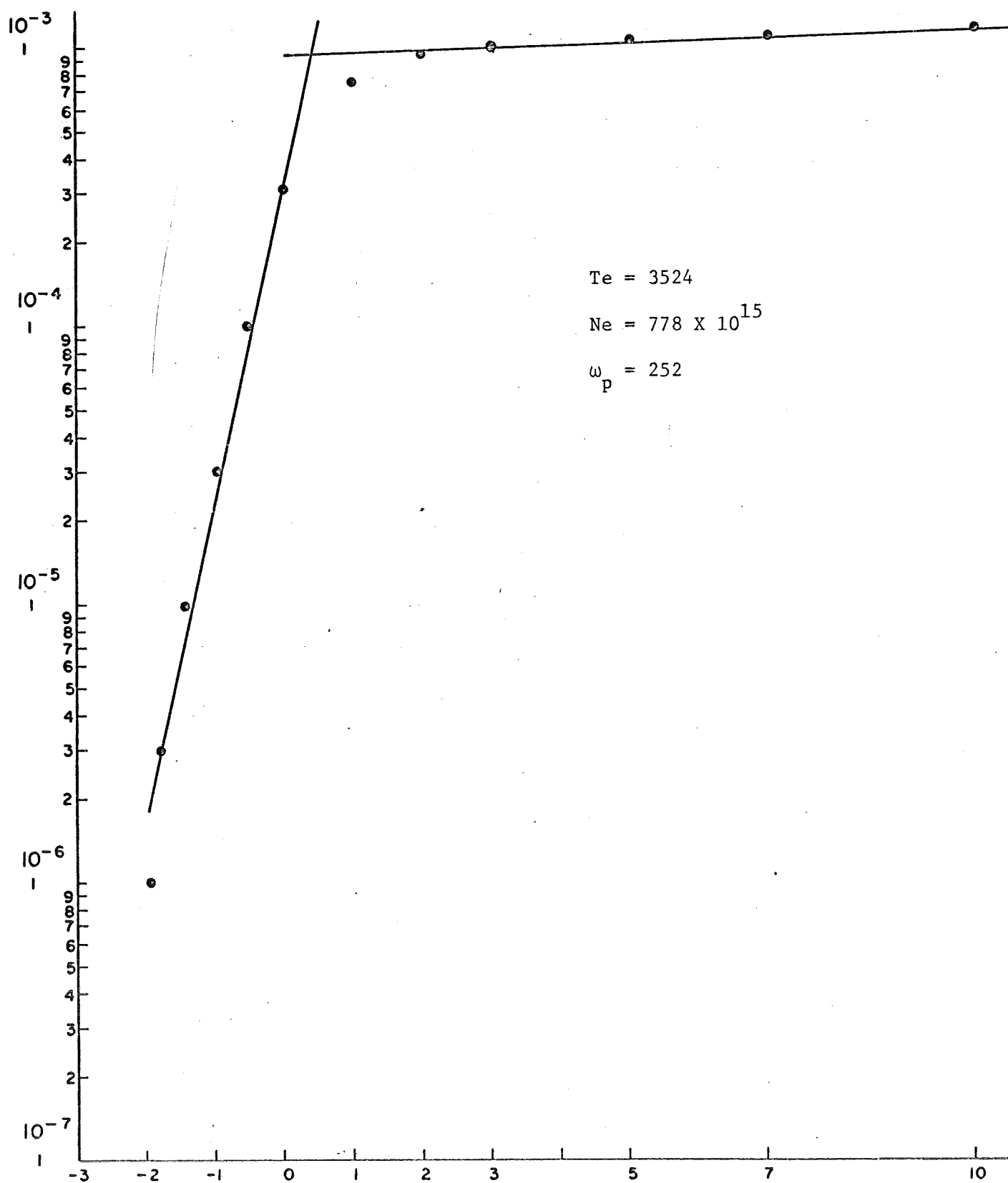
Te = 3524

Ne = 778 X 10^{15}

ω_p = 252

Figure 4

$x \, \mathcal{I}_B = 0$

$o \, \mathcal{I}_B = 5$

$\triangle \, \mathcal{I}_B = 15$

Orientation 45°

P = 100

I = 3

10⁻³

10⁻⁴

10⁻⁵

10⁻⁶

10⁻⁷

-2   0   2   4   6   8   10

10

Figure 5

11

Figure 6

Figure 6

B = 0 amp
BIAS = +1υ
400μ

Figure 7

B = 0 amp
BIAS = -1υ
400μ

Figure 8

14

Figure 9

B = 5 amp
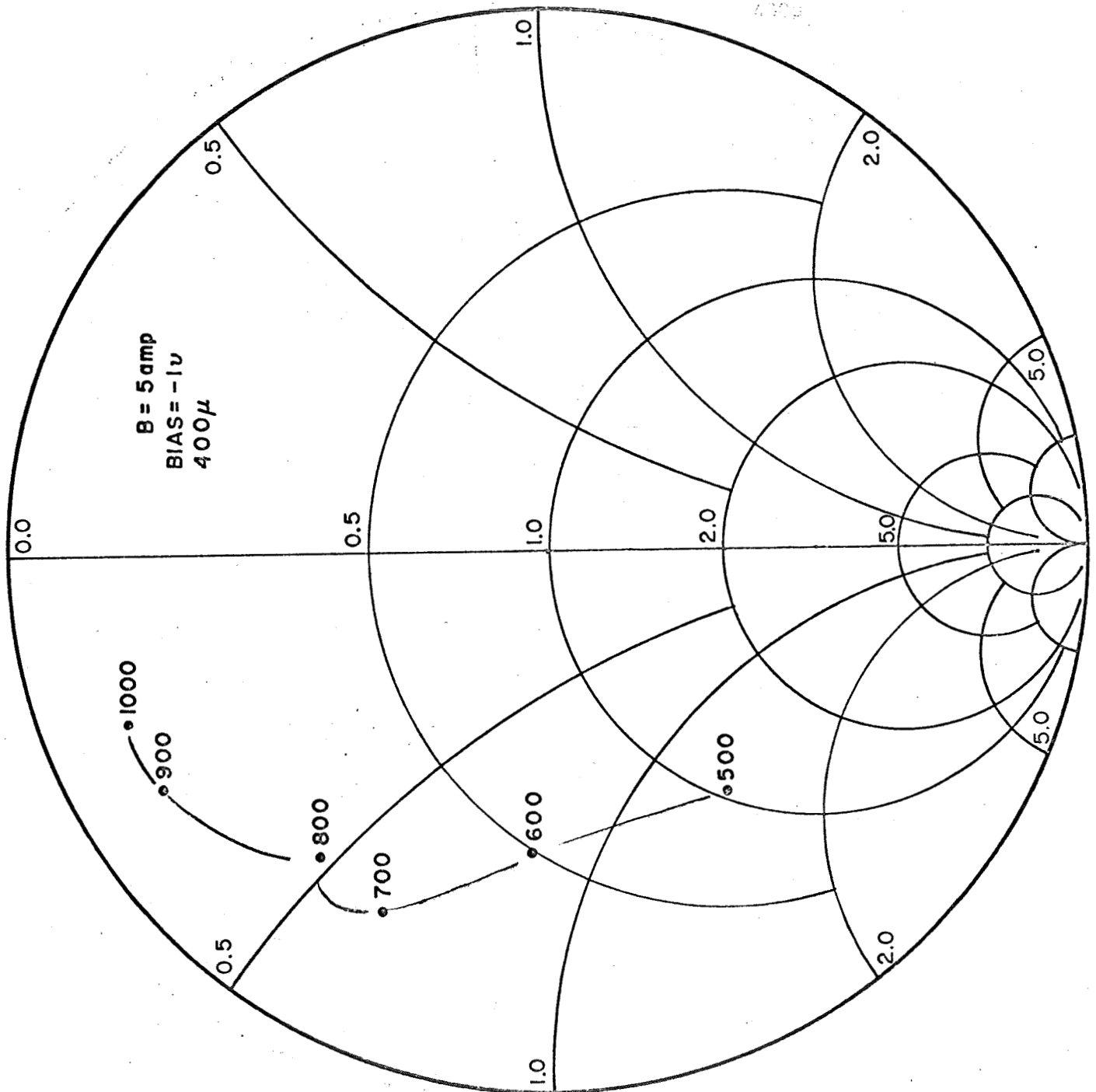BIAS=-1υ
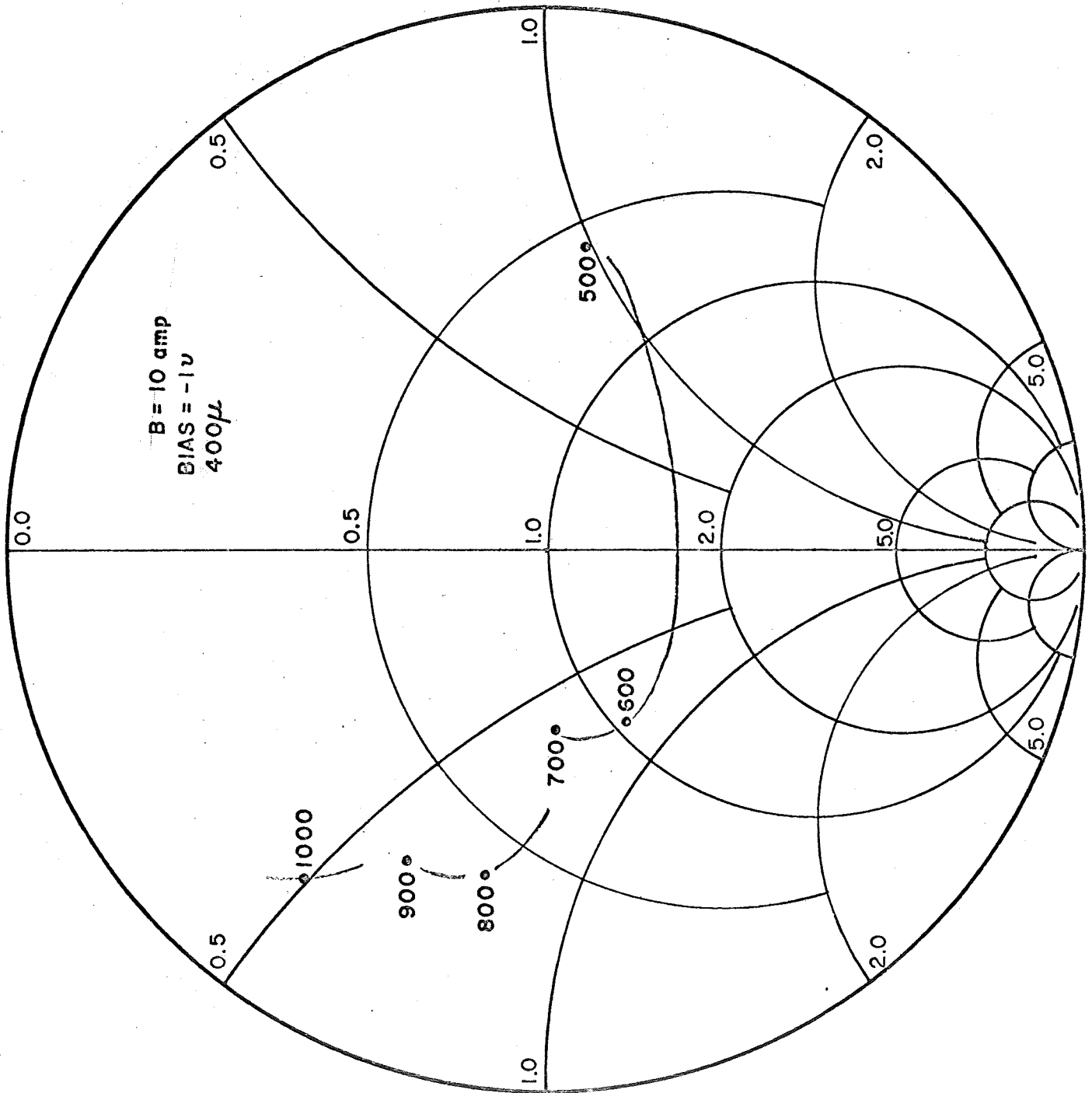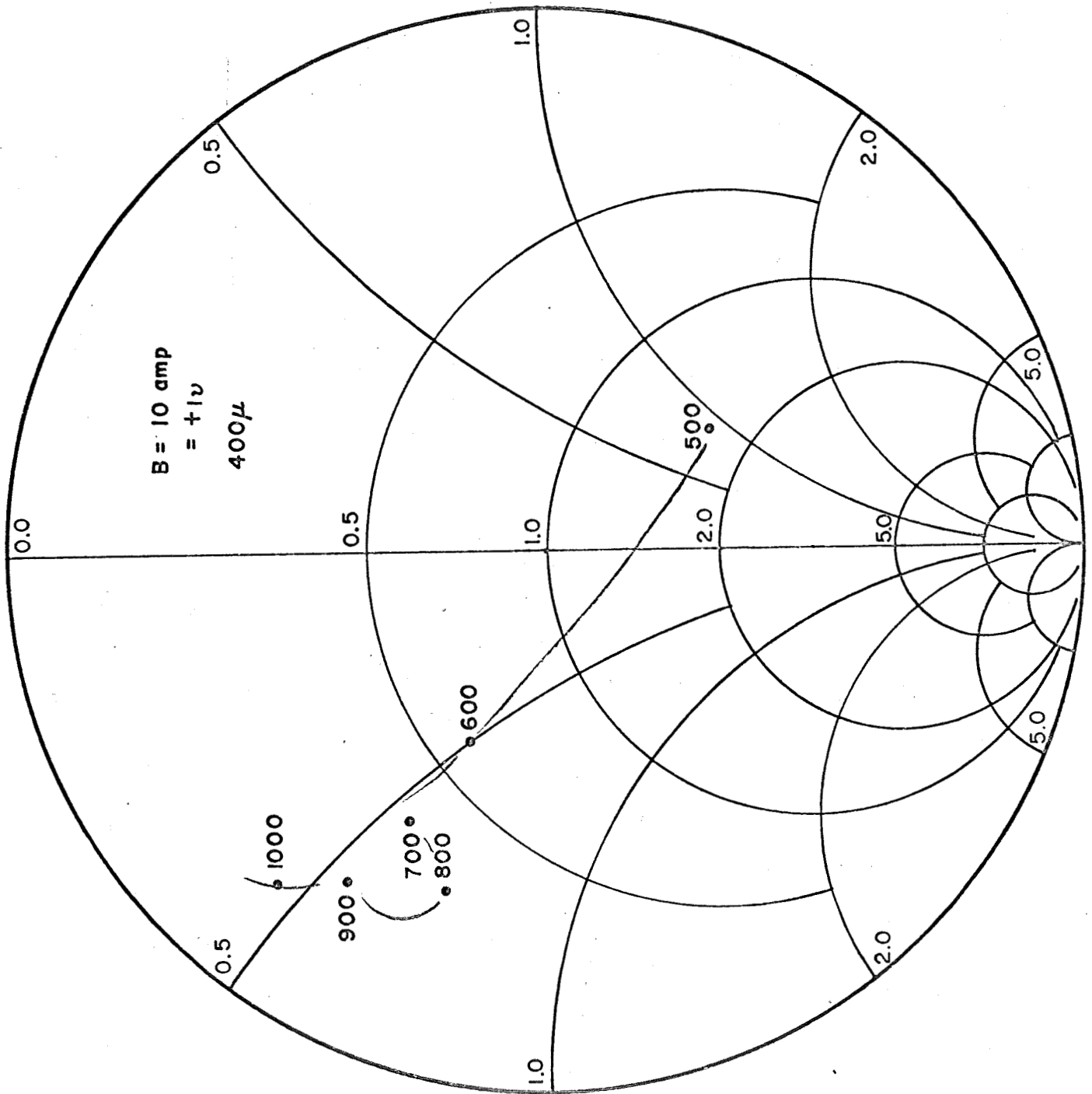400μ
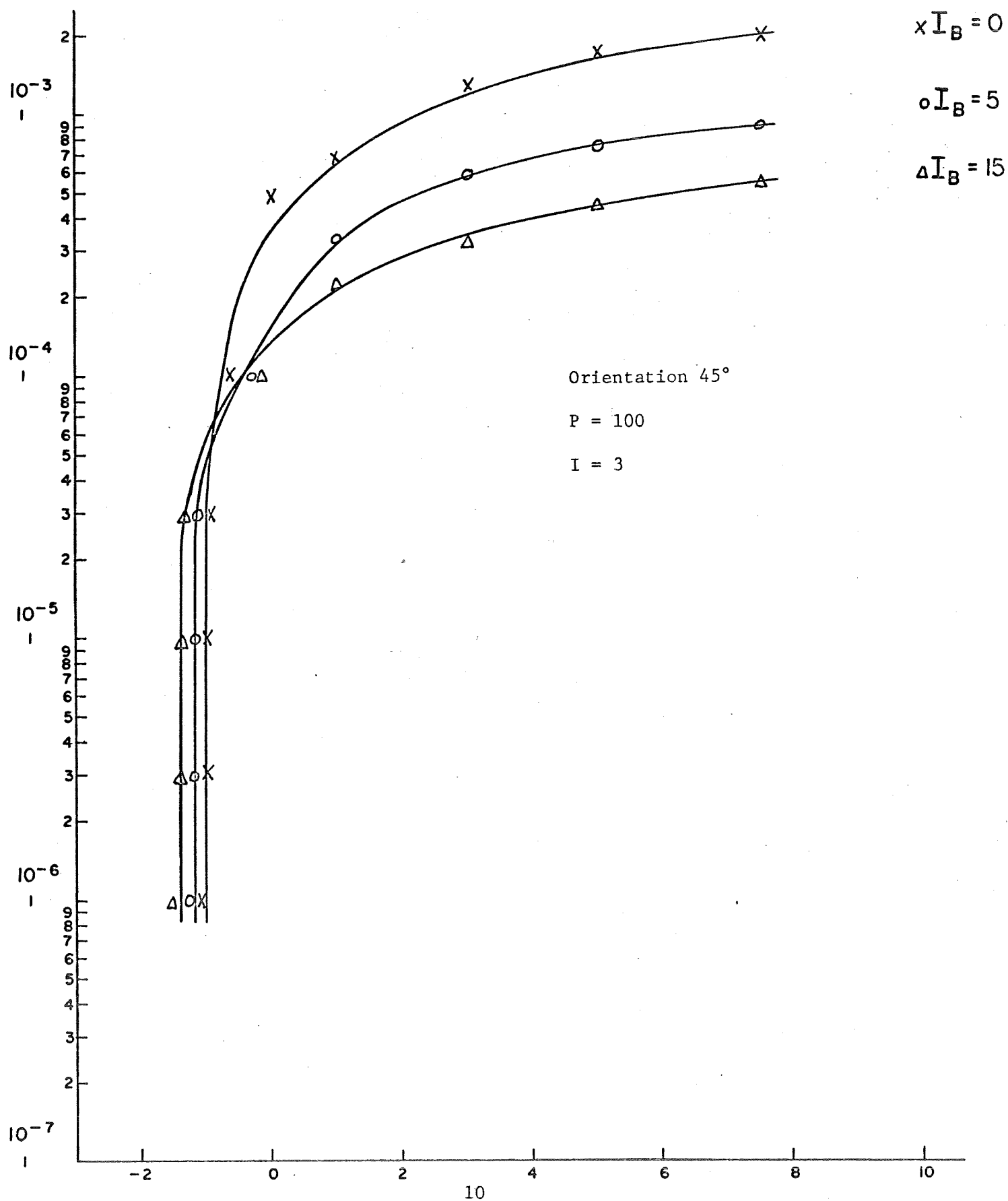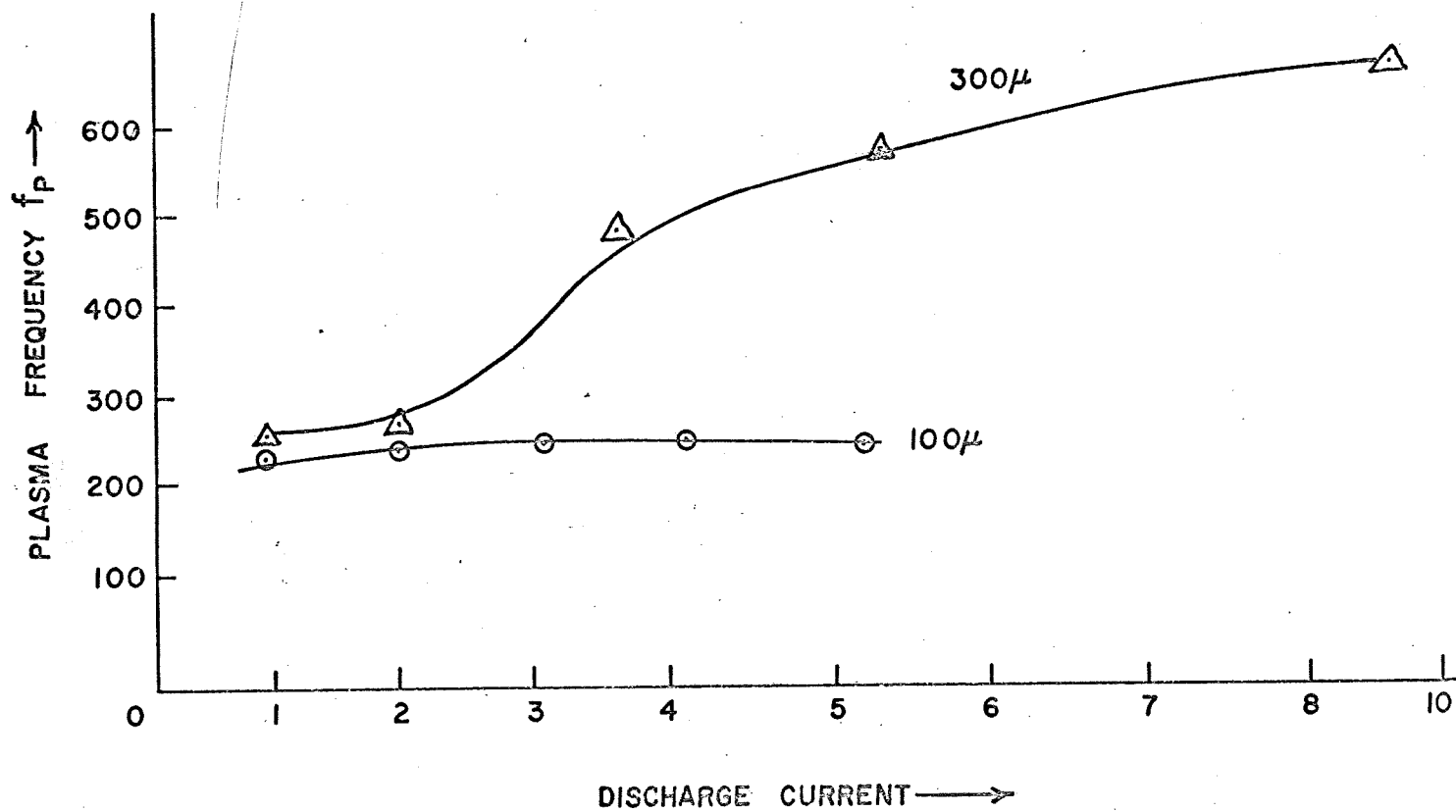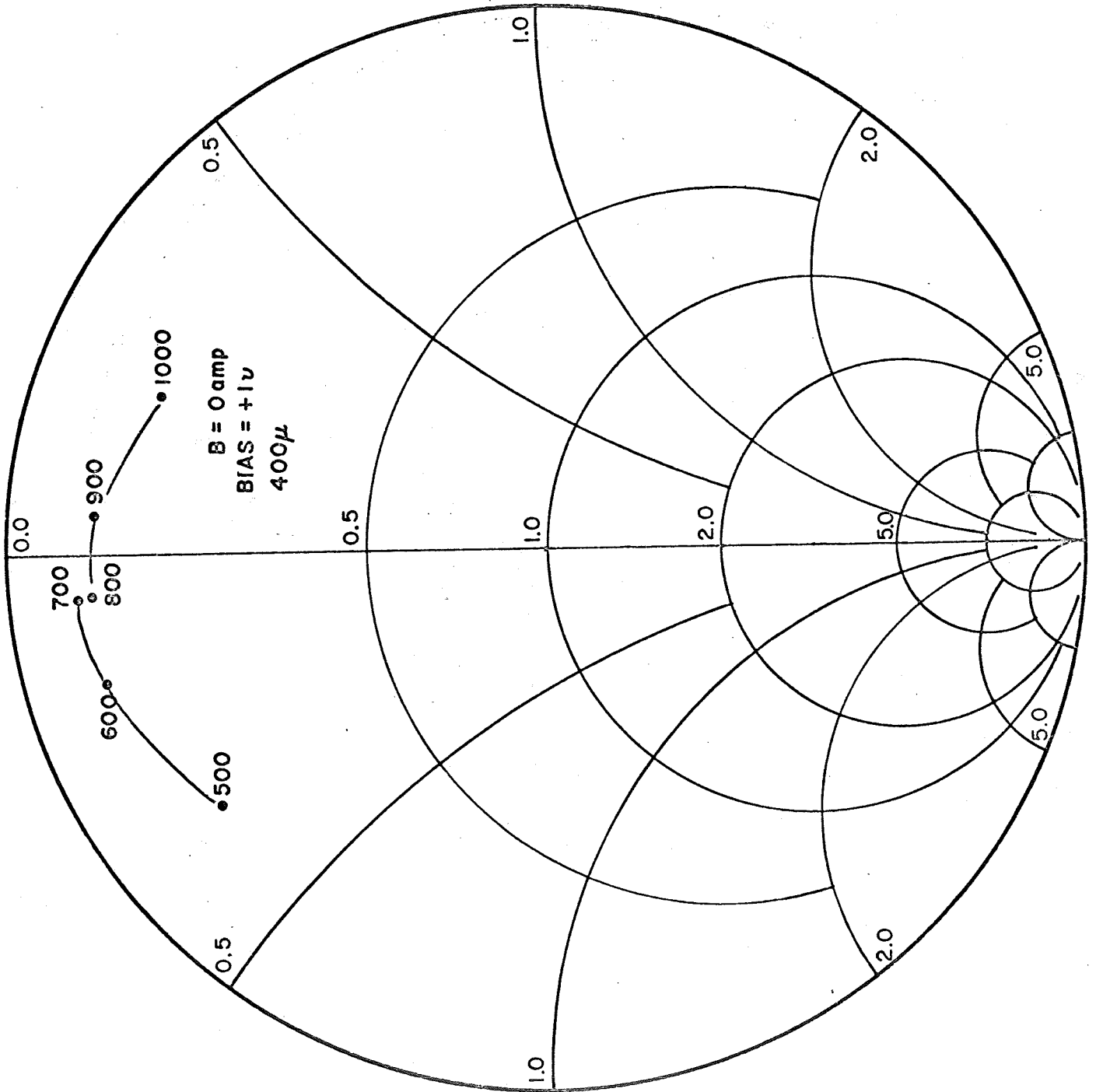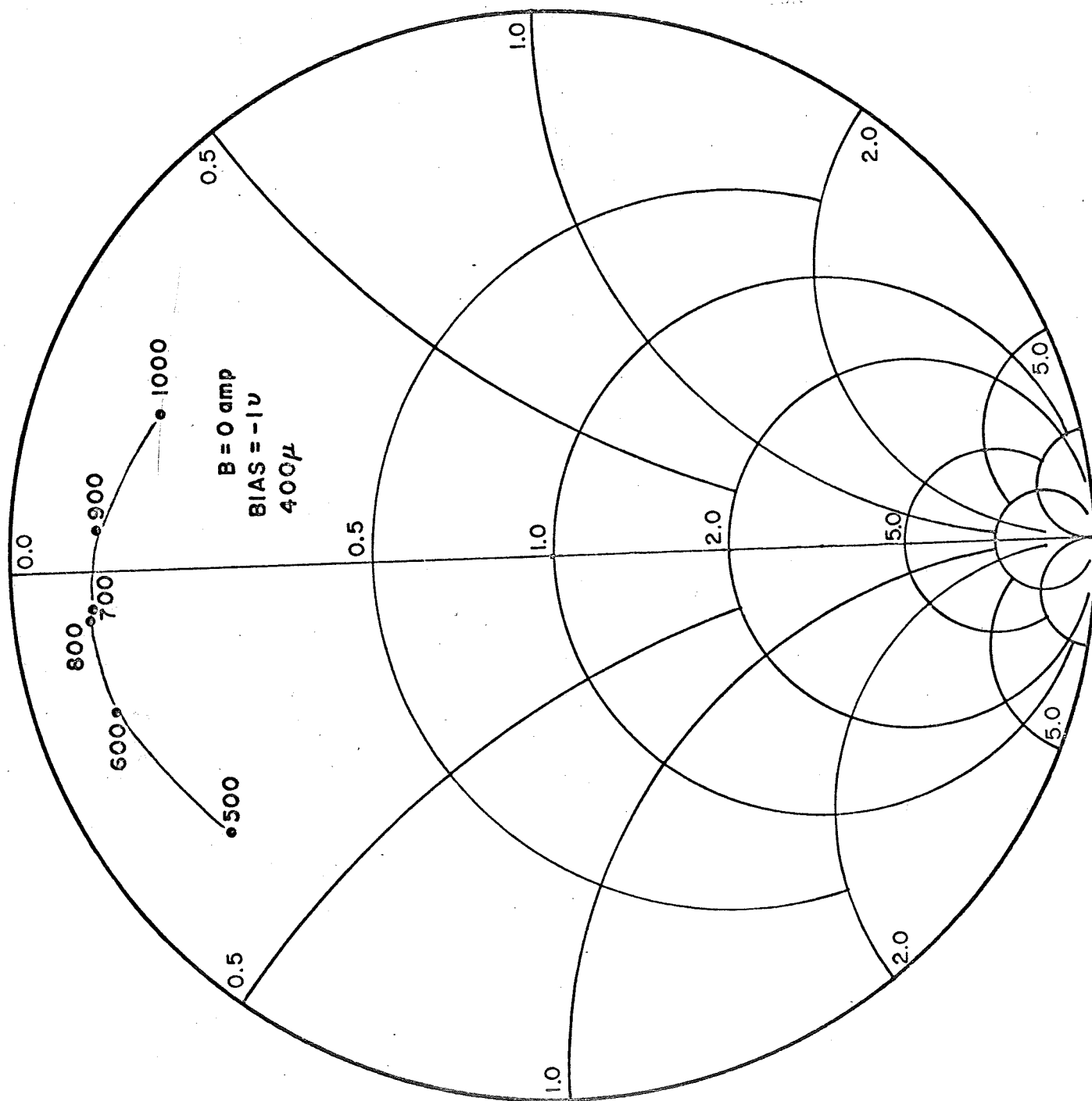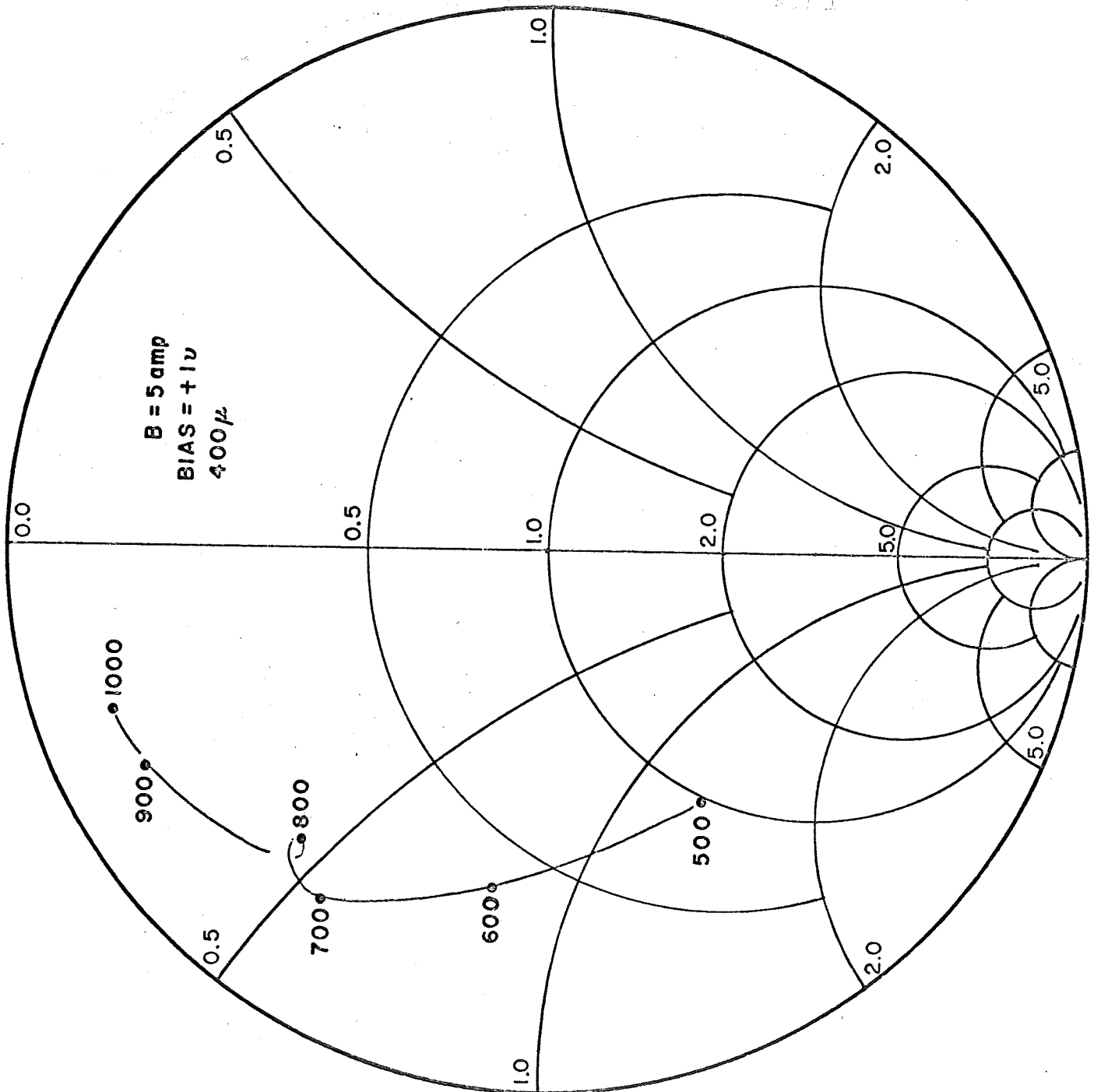
Figure 10

Figure 11

Figure 11

2.4   Radiation from a Parallel-Plate Waveguide into a Layered Plasma

    Medium - R. J. Kostelnicek and R. Mittra

    The work on this aspect of the problem is essentially completed.

Mr. Kostelnicek's thesis issued as Scientific Report No. 12 is now

being revised and condensed in view of publication.

2.5   Experimental Investigation of Antenna Noise in Magnetoplasma -

    T. S. Wang and Y. T. Lo

    Mr. Tun-Soo Wang joined us in this project June 1969. During this

period, the major effort has been the design and construction of a

discharge tube and magnetic coils. At this moment the construction

work is near completion and it is expected that some measurement will

be started soon. A full account of this construction work is given

below.

    A brush cathode discharge tube was built to generate the plasma.

The brush cathode consisted of approximately 1600 tungsten rods brazed

on to a 3" diameter molybdenum plate. The rods were first sharpened

by electrolytic etching in KOH solution. These pins were held by a

carbon jig on the base plate while the whole assembly was brazed in a

hydrogen atmosphere furnace. The pins and the moly plate were both

nickel plated to insure a good brazing joint. After the needles were

on to the base plate, the nickel plating was etched off to avoid sputtering

inside the discharge tube.

    The anode was made of 304 stainless steel. Some holes were drilled

in the surface of the anode to increase its surface area. This is called

an inverse anode. Inverse anode has less tendency to give anode spots

than ordinary flat anode.

Both the anode and the cathode had three 1/8" stainless steel rods attached to the back of its base plates. These rods are used to provide electrical connections as well as supports for the electrodes to the discharge tube. Two circular pyrex glass plates were made and three small holes were drilled on each glass plate to fit the stainless steel rods at the back of the electrodes. Then, the electrodes were attached to the glass plates by using epoxy to seal the steel rods to the holes. Later the glass plates were put on both ends of the discharge tube and sealed with ton seal epoxy. (See Figure 1).

A small dipole antenna will be put into the tube through an O-ring joint at the side of the tube. This arrangement will allow us to rotate the antenna in order to change the antenna angle with respect to the external magnetic field.

A double-probe with two thin tungsten rods for measuring the electron density of the plasma is under construction. It will be inserted into the tube by using a quick coupling. The probe is removable.

The whole system is connected to a Vecco high vacuum pumping station. Pump-down is followed by sealing off the discharge tube then back-filling with helium. Back-filling can be controlled by a micrometer pin-valve and the helium pressure is checked by an Sutovac - Priani gauge which has been calibrated for helium by the manufacturer.

The external magnetic field is supplied by a pair of Helmholtz coils placed around the tube as shown in Figure 1. The actual Helmholtz coils should be in the shape of a frustum of right circular cone in order to satisfy the relation D = 1 (See Figure 2) for every turn.
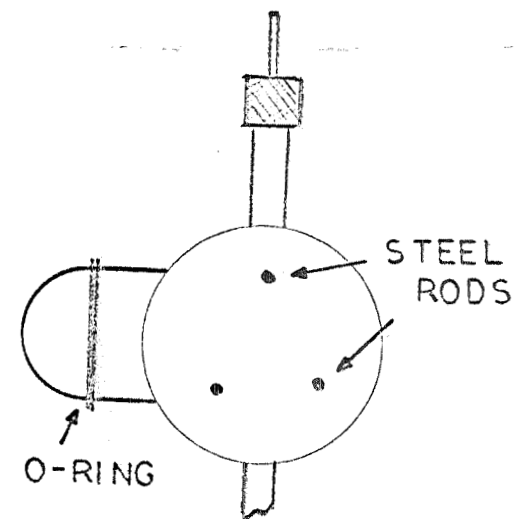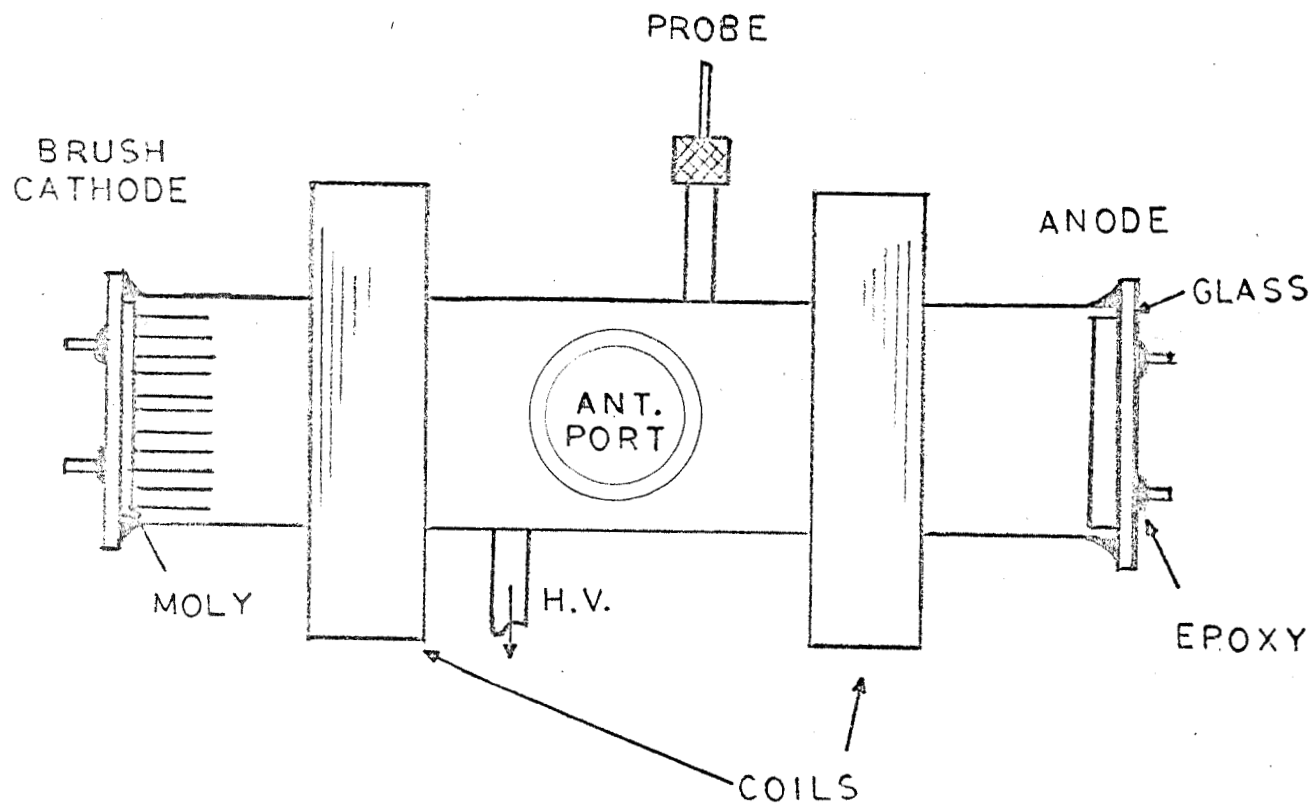
FIG. 1   PLASMA   TUBE
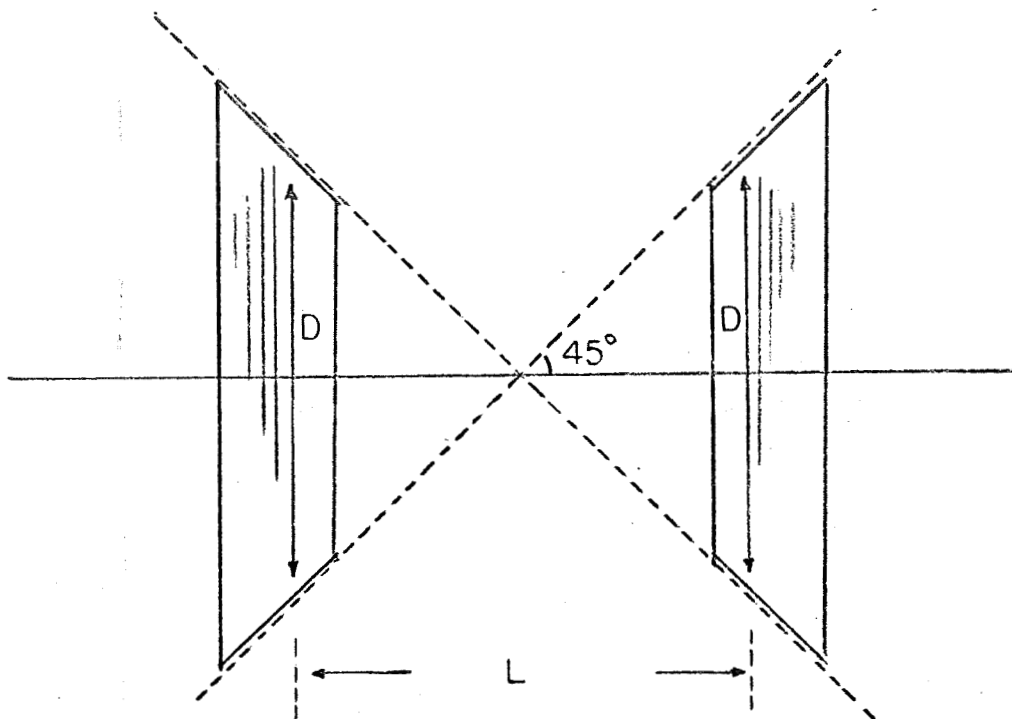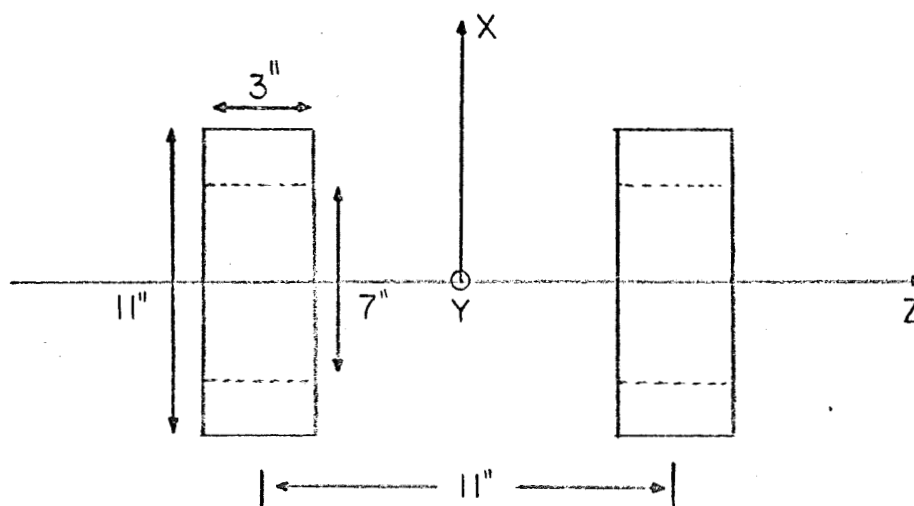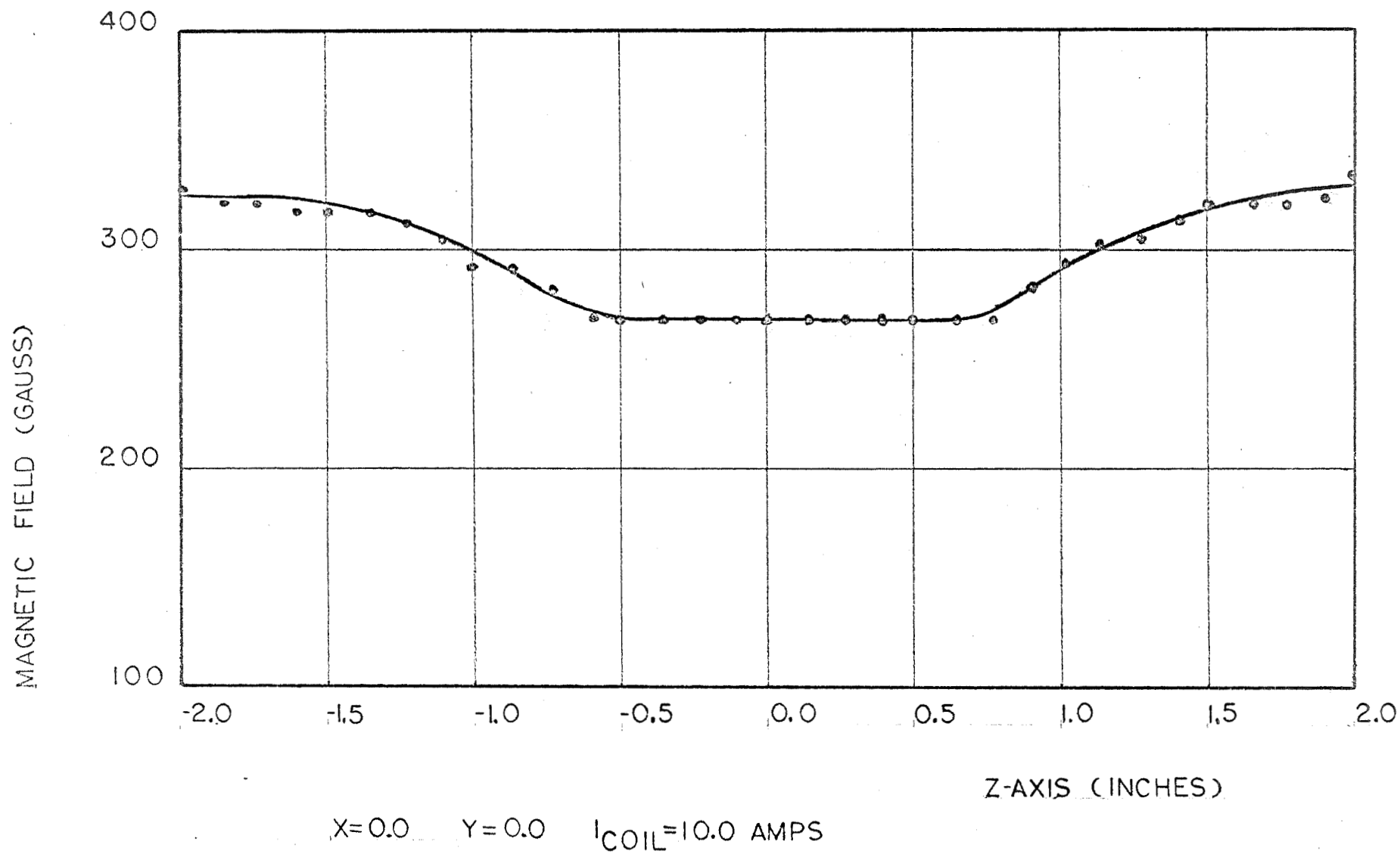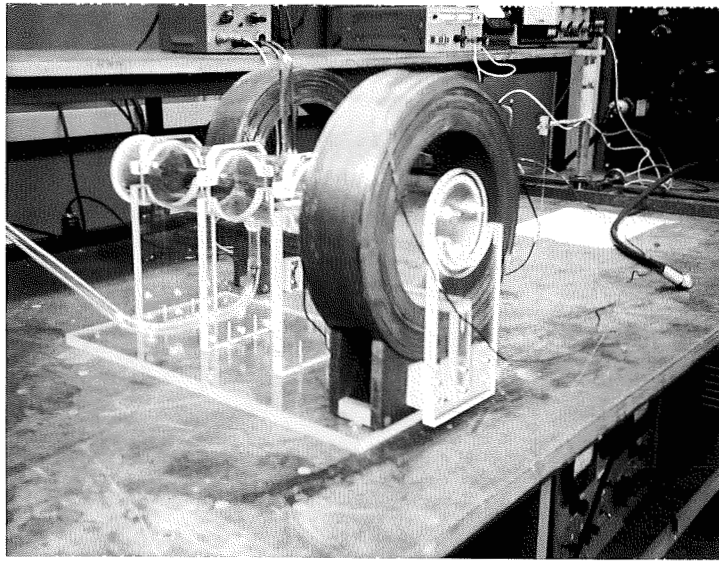
FIG. 2

FIG. 3

21

FIG.4 MAGNETIC FIELD ALONG Z-AXIS

X=0.0   Y=0.0   I_COIL=10.0 AMPS

Figure 5

We found that it was very difficult to wind a multi-layer cone shape coil, therefore we made the present coils as shown in Figure 3. The coils were made of No. 12 copper wire and each had 720 turns wound in 24 layers. The magnetic field was measured by using a Beckman Hall device. The maximum field strength without excessive heating is about 350 gauss. This figure can be increased if electric fans are used to cool the coils. The magnetic field near the center of these Helmholtz coils was found to be reasonably uniform. Some typical plots of field intensity are shown in Figure 4. The photograph in Figure 5 shows the entire assembly with the rear magnetic coil displaced in order to show the cathode structure.

2.6 <u>Diagnostics and Remote Probing</u> - R. Mittra, M. Mostafavi and

D. Schaubert

Two separate techniques are under investigation for remote probing of a non-uniform medium whose refractive index either varies continually or in a stratified manner. The first of these is based on a parameter optimization approach in which the inhomogeneity of the medium is described in terms of a set of unknown parameters. These parameters are next determined by computer search algorithms that seek to minimize a performance index function. The performance index P for this problem is defined as the norm of the difference between the reflection coefficient R for the actual medium and R' for a medium characterized by a trial set of parameters which are to be optimized. Thus

$$P = \sum_{n,m} \left| R(\theta_n, k_m) - R'(\theta_n, k_m) \right|^2 \qquad (1)$$

where θ_n is the incident angle of the plane wave and k_m is the free space wave number and the problem is to minimize P by varying the medium parameters. Both continuously varying and stratified media have been studied by Rosenbrock's optimization method with fairly good success. The method has also been successfully applied to radially inhomogeneous media. However, one basic difficulty with this method is that it only finds the local mimina of the function P and it is not possible to program the computer to automatically iterate to the desired solution. An alternative method, called the conjugate gradient method which is capable of systematically iterating to a more reliable minimum where both the function value and the gradients are minimized, is currently being studied for optimal solution of the minimization problem. Initial results indicate that the method is capable of yielding results with greater accuracy and for less amount of computer time.

A few of the inversion results obtained by the optimization technique are shown in Figure 1. It may be seen that the results are quite good for simple profiles. Tests are being conducted with more general profiles $K(x)$ to assess the reliability of this technique.

The second method for determining the characteristics of an inhomogeneous medium involves an iterative solution of a nonlinear integral equation

$$k^2 \int_o^L K(x_o) \, \psi(x_o,u) \, G(u,x_o) dx_o = a(u) \quad -1 < u < 1 \qquad (2)$$

Here $K(x)$ is the relative permeability of the nonuniform medium; $u = k \sin \theta$; θ = angle of incidence of the probing plane wave; k = wave number; $G(u,x_o)$ is known Green's function; $\psi(x_o,u)$ = wave

function in the nonuniform medium. The wave function ψ satisfies the equation

$$\psi'' + \{k^2 K(x) - u^2\} \psi = 0 \qquad (3)$$

and the boundary condition $\psi = 0$ at $x = L$. It can be calculated by a number of techniques if $K(x)$ is known. However, it must be regarded as a dependent unknown as far as (2) is concerned, since $K(x)$ itself is not known. One could, in principle, derive an iterative solution by assuming a $K_o(x)$, calculating the corresponding $\psi_o(x,u)$, solving for a new $K(x)$ by substituting ψ_o (2), and finally repeating the entire procedure n times until convergence is achieved. Runge-Kutta technique has been employed for obtaining $\psi(x,u)$ for a given $K(x)$ and matrix methods is used for subsequent solution of the integral equation. An investigation of this procedure has revealed that the matrix associated with the kernel of the integral equations is ill-conditioned, and hence, the chances for the success of the iterative method does not appear to be very promising. For this reason an alternate method is currently being developed to circumvent this type of difficulty. The new method allows the excitation of the solution by a direct technique that requires no iteration but only a single matrix inversion which can be effected in a closed form.

The method is based on the following analysis. Rewrite (2) as

$$k^2 \int_o^1 K(x_o) \; \psi(k,x_o,u) \; G(u,x_o)dx_o = a(u,k) \quad u_1 < u < u_2 \qquad (4)$$

Note that ψ and $a(u)$ have been written explicity as functions of the wave number k, and it is indicated that G and K are independent of this parameter. Now expand ψ and a in power series of k to get

26

$$k^2 \int_o^1 K(x_o) \left[\psi_o(x_o,u) + k\psi_1(x_o,u) + k^2\psi_2(x_o,u) = \ldots\right] G(u,x_o)dx_o$$

$$= a_o(u) + ka_1(u) + k^2a_2(u) + \ldots \tag{5}$$

Equating the powers of k on both sides of (5), one obtains

$$a_o(u) = 0; \quad a_1(u) = 0 \tag{6}$$

$$\int_o^L K(x_o) \, \psi_o(x_o,u) \, G(u,x_o)dx_o = a_2(u) \tag{7}$$

and so on.

Since $a(u,k)$ is a known function, (6) yields no new information.

However, (7) turns out to be in a form very desirable for determining

$K(x)$. This is because $\psi_o(x,u) = \lim\limits_{k\to o} \psi(x,u)$ is known exactly as may

be seen by reference to (3). In the limit $k\to o$, $\psi(x,u)$ becomes independent

of $K(x)$ and hence $\psi_o(x,u)$ can be determined exactly. It follows, then,

that the kernel $\psi_o(x_o,u) \, G(x_o,u)$ is a known function, and hence may

be inverted using conventional techniques, rather than by iterative

means which was required for resolving (2). The numerical behavior

of (7) is currently being investigated and the results will be reported

during the next period.

3. PUBLICATIONS AND TRAVELS

The literature survey on antennas impedance on a plasma will be

soon ready for distribution in report form.

C. Liang's thesis will also be issued as a report.

R. Kostelnicek's thesis has been submitted for publication to

Radio Science.

R. Kostelnicek attended the Conference on Environmental Effects on Antenna Performance in Boulder, Colorado, July 16-18, 1969 and presented a paper (co-authored with R. Mittra) on "Radiation From a Parallel-Plate Waveguide into an Inhomogeneously Filled Space".

G. A. Deschamps and R. Mittra attended the XVI General Assembly of URSI in Ottawa, Canada, August 1969.

4. FINANCIAL INFORMATION

Financial information is contained in the Quarterly Financial Reports submitted by the University of Illinois Business Office on Form No. 1030.
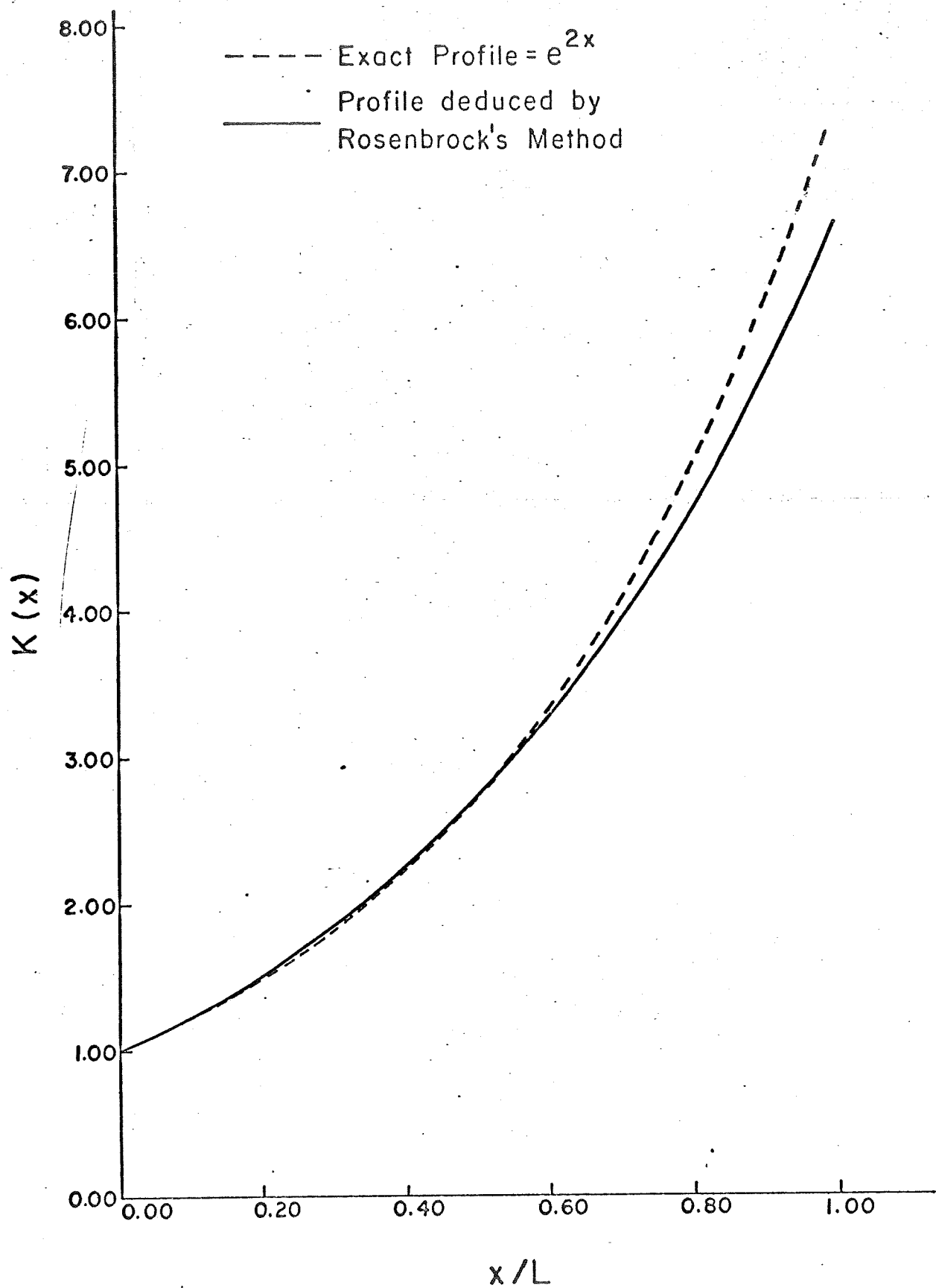
Figure 1.   Profile of dielectric constant K(x) for a slab terminated by
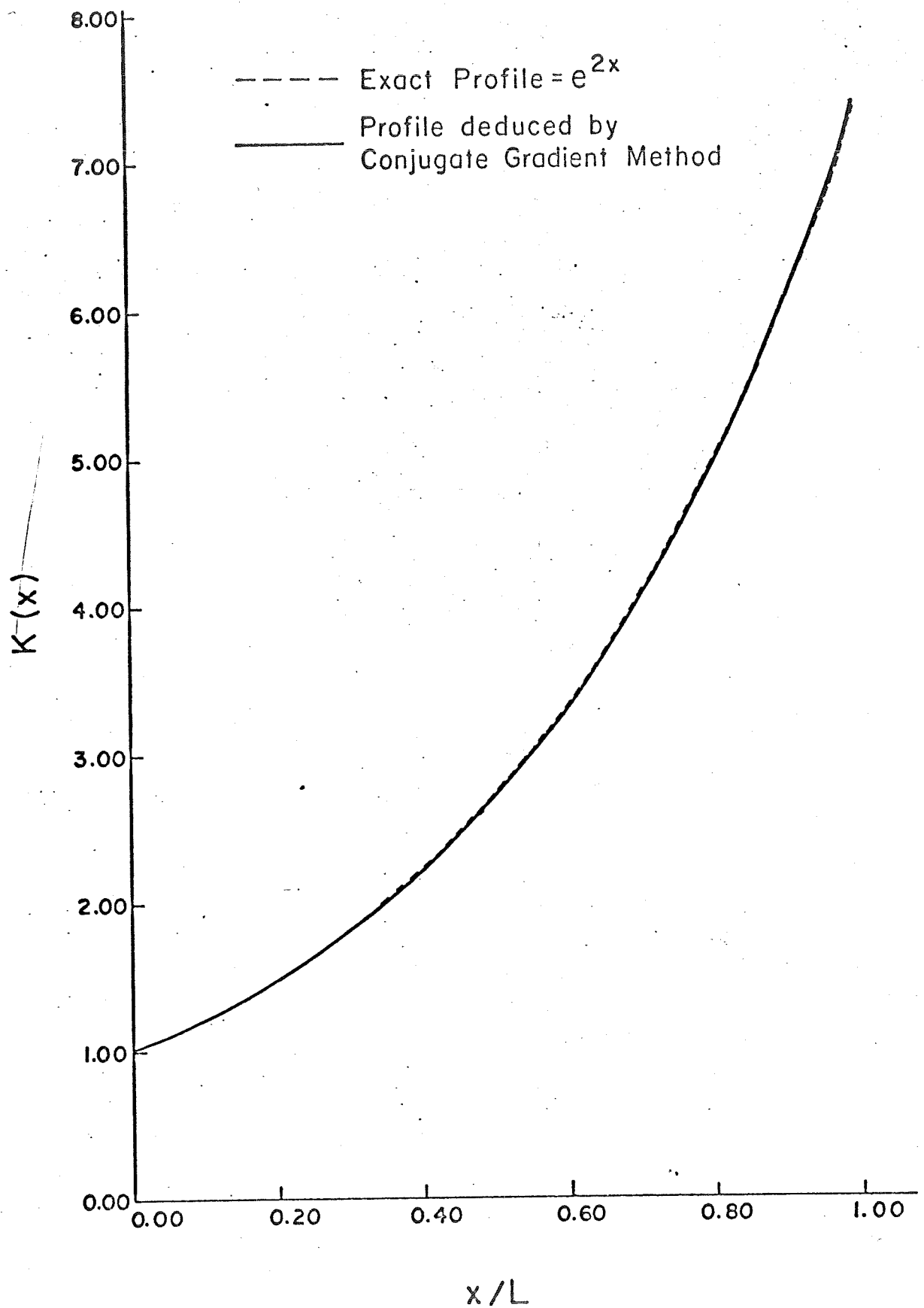a perfect conductor at x = L.   Rosenbrock's Method.

Figure 2. Profile of dielectric constant K(x) for a slab terminated by a perfect conductor at x = L. Conjugate Gradient Method.
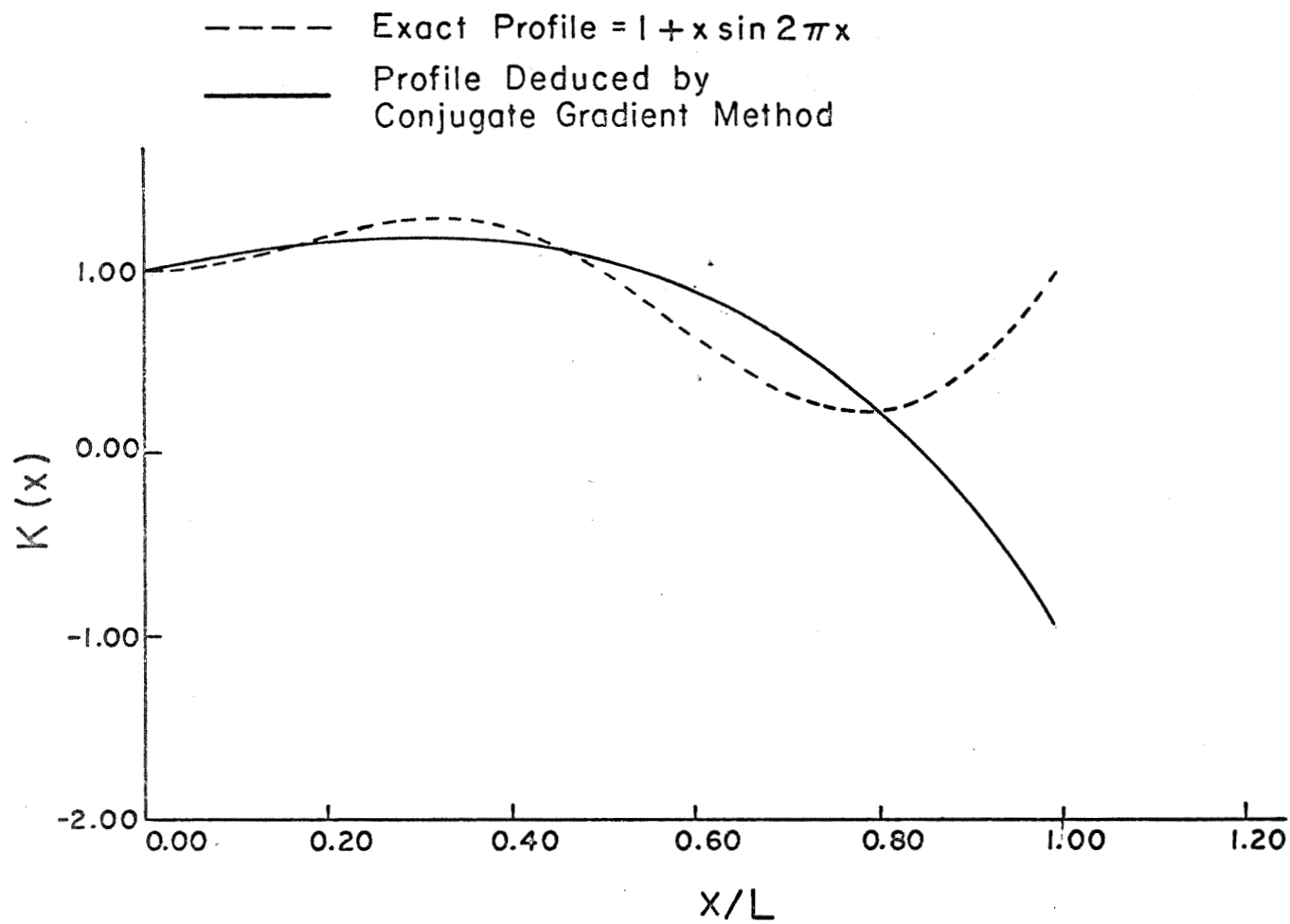
Figure 3. Profile of dielectric constant for a slab terminated by a
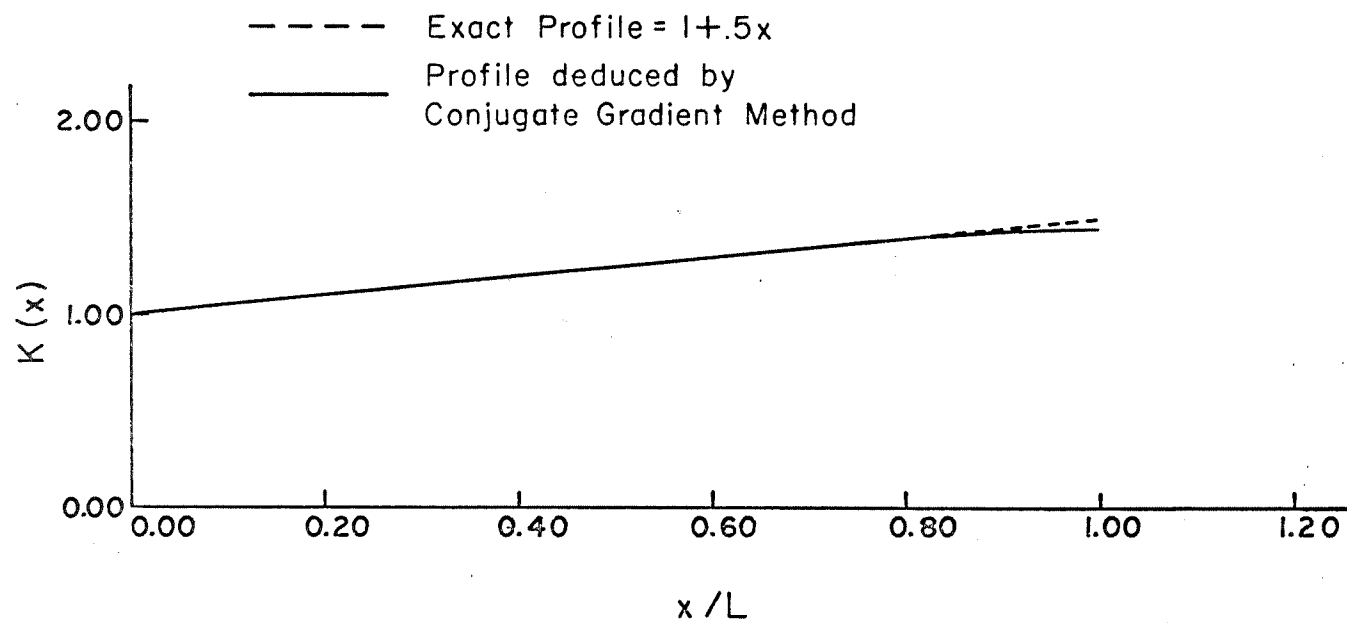perfect conductor at x = L. Conjugate Gradient Method.

Figure 4. Profile of dielectric constant for a slab terminated by a
perfect conductor at x = L. Conjugate Gradient Method.